

Article

Regenerative Belt Conveyor versus Haul Truck-Based Transport: Polish Open-Pit Mines Facing Sustainable Development Challenges

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Abstract: The mining industry is facing sustainable development challenges, among which the energy efficiency issues seem to be of major importance. As transport of the mined ore is considered as one of the most energy intensive operations, the improvement of its energy efficiency is a key indicator in terms of sustainable actions taken by mining companies. In open-pit mines, the material handling operations are mostly performed with trucks. Their electrified version—truck trolley systems—surpass diesel trucks’ efficiency while comparing the increased production capacity and the reduction of maintenance cost and fuel consumption. The paper analyzes the opportunities and benefits of the replacement of an ore transport system based on hauling trucks with a regenerative belt conveying in an open-pit mine. Presented case study has been analyzed from energy consumption and environmental impact reduction perspectives. Generally, conception of a regenerative conveyor is based on recuperation of energy or continuous braking needed while a conveyor is running downhill. Energy generated during the braking process (converted from the potential gravitational energy of the conveyed material) is fed back to the electrical grid. Then the regenerative conveyor can be considered as a machine that mines energy as an additional by-product of an exploited deposit. It was shown that difference in transportation cost between haul trucks and energy efficient regenerative conveyors is around 95%. The paper points the conditioning elements to allow the implementation of a regenerative belt conveyor system.

Keywords: regenerative belt conveyor; sustainable development; energy efficiency; open-pit mine; deposit of the potential gravitational energy

1. Introduction

Nowadays, the mining industry is forced to shift from conventional mining to a sustainable one, which makes sense for economic, environmental and social reasons. These three factors are considered to be of fundamental importance to balance mining operations within the whole mine life cycle [1,2]. Growing concerns about mining companies’ impact on their surroundings call for sustainability reports to provide transparent and comprehensive information about their sustainable activities [3,4]. The Global Reporting Initiatives (GRI) Standards framework is considered to be the most practical guideline for sustainable reporting (SR), as it reflects the positive and negative contributions of sustainable development in the company. Although the usefulness of the reports and quality of contained information have been the subject of criticism [5–7], SR improves corporate image as well as the social and environmental performance of the company. Since the Polish mining industry is amongst the strongest in the European Union—the top 10 producers of primary aggregates [8],

the leader of phasing out European hard coal production [9] and finally the leading country in copper production [10]—the necessity of implementing sustainable solutions in Polish mines is crucial in order to meet the international standards for responsible mining activities. The aggregates production in Poland for the last 30 years has boosted to match the demand from the extensive infrastructure development—since 1990 in the adjacent East Germany lands and also within Poland being entered into the EU, after implementing the EU structural funds.

In the recent years, authors [4,11–13] have identified and evaluated sustainable practices of selected mining companies in Poland. It seems that guidelines for sustainability reporting are considered as a set of best practices that are more and more often implemented not only by large mining companies but also by small and medium-sized ones for which their public perception is essential. In accordance with [14] the most relevant and widely analyzed segment of sustainability in mining is its environmental performance. Aspects such as gas emissions, noise pollution and especially energy use are attracting widespread interest. In general, the metal ore and rock resource mining industry is considered as an energy intensive one and it is estimated to consume 6.2% of the total global energy consumption [15]. According to [16], the final energy consumption of the Polish mining industry accounted for 12.30% of the final consumption of the European Union mining in 2017. Such an energy intensive industry sector needs to be scrutinized from a sustainability and energy-related policy perspective.

The sustainable development concept of the energy issues in the mining industry is aimed at initiatives for the improvement of operations' energy efficiency and the use of clean energy. The implementation of technologies that minimize the energy consumption of comminution processes [17,18], loading and hauling operations [19,20] or mine ventilation [21,22] are key actions dedicated to the sustainable use of energy. Moreover, renewable energy use, energy management systems and strategies are becoming increasingly important for energy savings [23–25]. Comprehensively designed energy systems and deployment of renewable energy systems enables model energy demand, control on electricity consumption and finally, leads to cleaner production.

Furthermore, as current European Union policy in the field of Energy and Environment is aimed at energy efficient and environmentally friendly operations, directives and regulations for energy efficiency were put in force by the EU Energy Efficiency Directive [26] and amending Directive on Energy Efficiency [27] which constitutes the policy framework and measures for efficient use of energy in the EU. The noteworthy part of government legislation is energy labeling and eco-design regulations [28]. The main objective of energy labeling is to provide an accurate information about energy efficiency of a product and some features of its usage, including noise emissions. This means that users may compare energy-related products and choose those that are better-performing. Next, eco-design requirements set the mandatory minimum standards for products' energy consumption to enhance its environmental performance over its entire lifecycle. Considering these trends energy-consuming mining equipment, e.g. belt conveyors, should no longer be designed and built to the outdated and conservative standards. That is the reason for which, the proposal of new standards for belt conveyors has been presented in [29]. The idea of standardization assumes to create energy labels and take a holistic perspective on designing conveying systems.

Taking the above into consideration, the sustainability concept is in line with energy-related policy framework. Thus, the efficient use of energy seems not to be a matter of choice but an absolute necessity, especially for energy-intensive mining operations, amongst which material handling is of great importance. The aforementioned massive aggregates production in Poland is located mostly in the southern, mountainous part of the country (see Figure 1). Such location gives an opportunity to recover the potential gravitational energy of tons of run-of-mine material in the case of transporting it downhill. The sustainable approach assumes that apart from a deposit of aggregates, a *deposit of potential gravitational energy* (a sort of by-product) should be evaluated and effectively “mined” with the use of appropriate equipment—a regenerative belt conveyor.

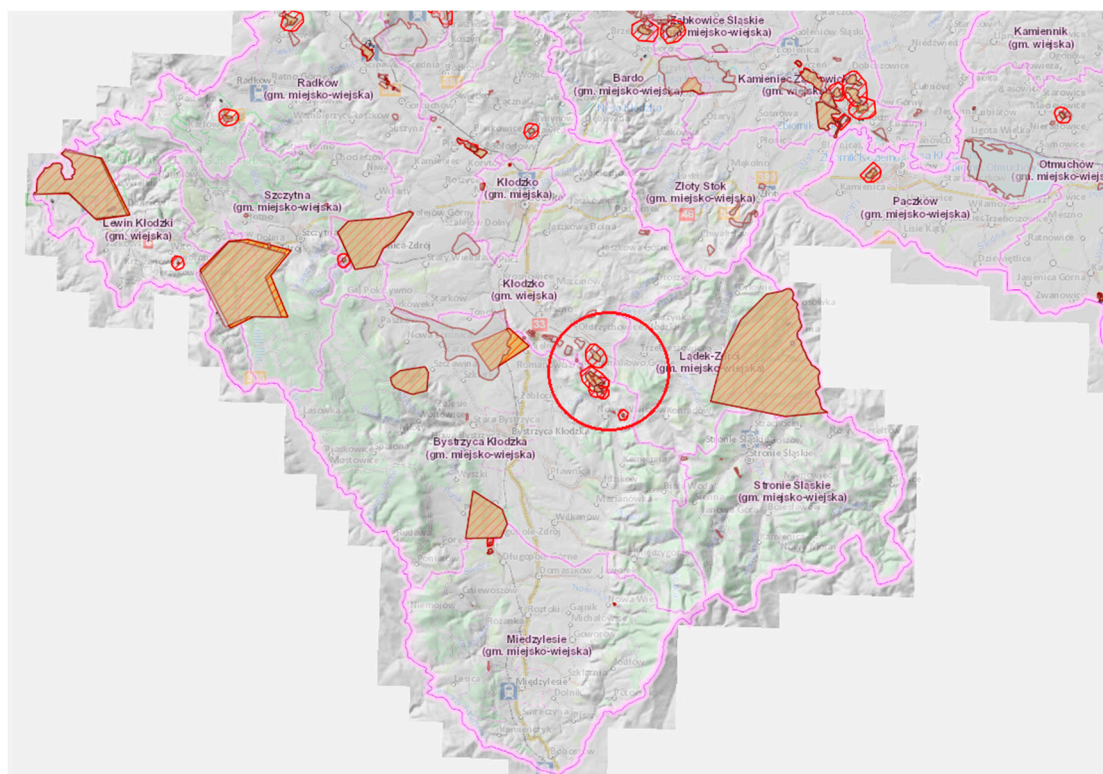


Figure 1. Active aggregate mines and prospective deposits in the Kłodzko Valley in Lower Silesia (Southwest Poland at the Czech Republic border) [30].

2. Materials and Methods

2.1. Materials Handling—Energy Intensive Operation

In accordance with Soofastaei et al. [31], the energy consumption due to material handling constitutes around 20% of the total energy usage in the mining industry. The mostly used mode of transport in open-pit mines are haul trucks, for which the main source of energy is diesel fuel [32]. When it comes to diesel fuel consumption, it is estimated to account for 40% of the total energy use and to generate even up to 50% of maintenance costs in open-pit mines [20,32]. Additionally, the environmental impact of haul trucks is recognized as negative and the reason is twofold. Firstly, consumed fuel causes greenhouse gas (GHG) emissions. Secondly, haul truck operations are the source of noise, dust, vibrations and local roads deterioration.

The energy efficiency of hauling operations depends on operating conditions, equipment unit efficiency and operator skills and practice [19]. Since various parameters influence fuel consumption, a neural network model was implemented to predict specific fuel consumption and maximum truck velocity was recognized as the most influential parameter [31]. Peralta et al. [33] showed that truck reliability, distance and weight are important for fuel consumption and a truck maintenance plan is vital for energy consumption and GHG emissions reduction. Another research proved that a 10% decrease in engine load factors results in significant CO₂ emission and fuel consumption reductions, as well as associated potential savings [34]. Moreover, hybrid electric vehicles are becoming an alternative for conventional haul trucks. Although the hybrid electric powertrain technology may improve fuel efficiency, the essential elements are drive cycle profile, constantly changing conditions and hybrid control system [35]. The relevant constraint of dump trucks energy performance are operator's skills, which directly influence parameters such as vehicle speed and cycle time during operation [36]. Some research has compared the traditional shovel-hauling truck system with in-pit crushing and conveying systems while analyzing the optimal transportation system in surface mines [32,37].

Truck haulage is flexible and may be well suited on an ongoing basis. On the other hand, belt conveyors operate at a lower decibel level (70 dB at 5 m distance) than trucks (90 dB at a distance of 10 m), minimize amount of emitted dust, reduce overall auxiliary equipment requirements and finally their (valuable) operating time is 25% higher than for haul trucks.

2.2. Trolley Trucks and Belt Conveyors Developments

Advancements in haul truck transportation are aimed at energy consumption reduction which directly lessens environmental impact. Therefore, the idea of mining haul trucks powered with diesel-electric engines and operating on trolley systems has been proposed. The general idea is to implement the trolley truck concept for hauling operations on ramps and diesel-powered ones for the remaining haul cycle [38,39]—such a solution is considered as the most effective one. It is worth to note that, in a situation where trolley assist systems work on downhill routes, the energy feedback to the grid is possible. It is observed that an important effort has been made for mining haul trucks operated on trolley systems, especially in the development of an integrated electric-mechanical model of a diesel-electric truck [40,41]. Valenzuela Cruzat and Aníbal Valenzuela [41] modelled and evaluated advantages of truck trolley systems for uphill and downhill paths for a copper mine. Obtained results show the increase in truck's speed (44%), reduction of its travel time (16%) and fuel savings (85%) on each up-down cycle. Another study points that diesel-trolley trucks are a beneficial opportunity for open-pit mines, because they tend to reduce the cost of rock mass transportation by 15–20% [42]. Another benefit is the reduction of fuel consumption by 50–60% and up to 1.7–2.0 times of pollution emission in comparison to diesel haul trucks. Advantages of a truck trolley system implementation are the increase of production capacity and the reduction of maintenance cost and fuel consumption. Generally, the solution enables production level requirements to be met and reduces the cost per ton of hauled material.

Alternative belt conveying systems are largely used as a technology for material transportation in the mining industry—high efficiency, reliability and durability make them competitive with haul trucks [19,20,43]. However, conveyors consume the significant proportion of power supply and contributes considerable part of costs in mines. In a Polish continuous-surface lignite mine, it was estimated that 50% of the total energy consumption was consumed by the over 120-km belt conveyor system [44]. Belt conveyor system cost is up to 40% of an operational cost and 12–15% of a mining production manufacturing cost [45,46]. Therefore, both theoretical and experimental research is aimed at new energy efficient solutions for conveying systems [47,48].

The majority of research on energy savings in belt conveyors operations is focused on equipment and operational level. When it comes to idlers, optimized space intervals [49], decreasing of rolling resistance [50] and idler intelligent garlands [51] have been analyzed. In the case of conveyor belts, the main attention has been put on its indentation resistance [52] and improvement of its structure and rubber compounds [53]. For drive systems, a selection diagram for an efficient drive configuration and design approach for multiple drive belt conveyors have been developed [54,55]. The operation efficiency of a belt conveyor is improved by adjusting the belt speed to the quantities of transported material. However, to optimize feed rate and belt speed while reducing energy consumption, the energy models of belt conveyors are of great importance [46]. Modelling energy requirements of belt conveyor systems with regard to dynamic loading was evaluated by Halepoto and Khaskheli [56]. A belt conveyor analytical model for optimizing its operating parameters such as operating efficiency, load shifting and operation scheduling was proposed by Zhang and Xia [57]. The methodology for optimizing conveyor speed was established in a range of works [58–60] and proved that speed control systems may result in energy and environmental benefits e.g. active speed control implementation may result in hourly energy savings of 16.21% for an 8 h dual belt conveyor system operation.

2.3. Measures of Mining Transport Energy Efficiency

While comparing the energy effectiveness of various transportation systems, the specific energy consumption (SEC), expressed in amount of energy needed to move a unit of mass of transported material for a distance unit, is widely used. However, it has to be noted that for any mine site, transportation costs are generated from moving run-of-mine material between workplaces of consecutive operations—from an excavation site departure (point A) to a depot (point B). Transportation route layout for trucks, rail vehicles and belt conveyors, in accordance with the appropriate industry standards, differ from one another. The allowed inclination for a railroad is limited to only 2.5%, for a road for trucks, up to 12%, while a conveyor route can be inclined up (or down) to 25%. Considering also the relations of allowed curvature of transportation routes (which can be replaced with a transfer point in a case of belt conveyors), the following relations apply to actual routes lengths $L_{A,B}$ at any given mine site:

$$L_{A,B} \text{ (belt conveyor)} \leq L_{A,B} \text{ (truck)} \leq L_{A,B} \text{ (rail vehicle)} \quad (1)$$

For the most inclined routes, a railroad is at least 5 times longer than a truck road and 10 times longer than a conveyors route. Therefore, apart from SEC, the site SEC ($SSEC_{A,B}$), expressed in amount of energy needed to move a mass unit of transported material from the point A to the point B along the transportation route that is specific for the mode of transport, should be compared.

$$SSEC_{A,B} \text{ (mode of transport)} = SEC_{A,B} \text{ (mode of transport)} \cdot L_{A,B} \text{ (mode of transport)} \quad (2)$$

The SSEC depends on the actual inclination of the route, operational capacity and parameters of a given transportation mode. The energy savings in mine transport can therefore be achieved either by improvements of haulage equipment or by appropriate delineation of its transportation route.

2.4. Accurate Modeling of Belt Conveyors

The calculations of the amount of energy needed for belt conveying should be based upon advanced calculation methods of resistances to motion and required drive power rather than simplified and conservative standards—CEMA, DIN, ISO [29]. The main resistances to motion methods are developed on both the theoretical analysis of physical phenomena that occur in the running belt conveyor (with the use of physical equations of loads, tensions, displacements and deformations rather than dimensionless, controlled by empirical constants, equations adopted in simplified standard methods) and the laboratory tests and in-situ measurements [61]. Such approach allows to evaluate the impact of a belt conveyor route layout, mechanical properties of a belt, idlers and transported material volumes on the actual resistances to motion. The theoretically proven and verified calculation methods of belt conveyor resistances to motion are capable to deal with any belt conveyor installation. These methods with the object methodology—inheritance of objects and virtual methods [62]—have been implemented in the in-house software QNK-TT by the domestic engineering software company Entertech, which is successfully used for the accurate modeling of a belt conveyor operation [63,64].

The QNK-TT software was used in this paper for digital experiments to model and analyze the actual energy demand by a belt conveyor in the given operating conditions.

2.5. Opportunities of Recuperation of a Potential Gravitational Energy of Hauled Tonnages of Mined Material by Belt Conveyors

Optimization of belt conveyor construction as well as organizational and technical improvements of bulk material transportation are vital for reducing energy consumption. Nevertheless, it seems that not only solutions which generate energy savings are relevant but also these which generate energy itself. This means that the development of an energy recovery system for belt conveyors is of great importance with regard to sustainable development rules. The idea for using regenerative drives for downhill conveyors and optimal scheduling models was proposed by Mathaba and Xia [65]. Generally,

the conception of a regenerative conveyor is based on regenerative or continuous braking needed while conveyors are running downhill. Energy generated during the braking process is fed back to electrical network when using an AC drive or to other driving motors while connecting their AC drive and DC busbars together [34]. This solution seems to be a beneficial improvement in existing downhill conveyors. However, the replacement of an existing haul truck transportation technology with a belt conveyor, especially the regenerative one, provides an improvement of material handling operation in both energy and environmental performances.

Following trends of sustainable development, the solution of recovering the energy can be used in some open-pit mines, in which aggregates are excavated from the ground. The average annual production of aggregates in Polish mines is around 300 million tons [8,66]. In Poland, open-pit mines are often located in hilly terrain and mineral deposits are excavated using hillside excavations. As a consequence, aggregates are transported from extraction site downhill to an aggregate storage area. However, the most commonly used types of transport are haul trucks [67], because of their flexibility and outsourced maintenance. The replacement of such transportation systems with conveyors would result in energy and environmental improvements in mines, which is analyzed below.

3. Results and Discussion

The presented case study examines the possible replacement of a hauling truck with the regenerative belt conveyor in the actual, chosen aggregates (here: dolomites) open-pit mine, where material is transported from the pit (opened typically on the peak of the hill) to the storage area located 43 m below. In Figure 2 the regular dump truck road is presented by a blue line while the analyzed alternative way of transportation is marked in red. The length of the existing truck road is 1500 m whilst the length of the conveyor is 645 m with an inclination angle of -3.83° . The annual production is around 100,000 (metric) tons and the optional storage bunker at the pit departure station is taken into account. The created map of the drive power range for a decline conveyor (presented in 3.1. subchapter) shows the optimal areas for recovery of energy. Then, the analysis of energy recovering was performed for two alternative conveyors: an energy efficient conveyor and a typical conveyor. Finally, the environmental impact of the proposed deployment has been calculated.



Figure 2. Visualization of the alternative haulage route for trucks (blue line) and for conveyor (red line) for the chosen, actual aggregates mine site (marked by the red circle in the Figure 1) [30].

3.1. Map of Drive Power Range

Belt conveyor drive power is a function of belt speed multiplied by the total belt conveyor resistances to motion, which is the sum of primary (main—acting along the whole conveyor route), secondary (occurring at specific points only—pulleys, cleaning devices, etc.) and gradient resistances (see Figure 3). It is worth noting that in the case of the downhill conveyor, the component which represents gravity force influences mostly the total motional resistance and the required power. Therefore, the effectiveness of energy recovery solution in belt conveyors depends on the belt conveyor inclination angle and tonnage of transported material. However, to indicate the areas of belt conveyor work, for which the implementation of the solution is justified, theoretical analyses of belt conveyor drive power range have been carried out. The assumptions for calculations made in the aforementioned QNK-TT software are presented in Table 1.

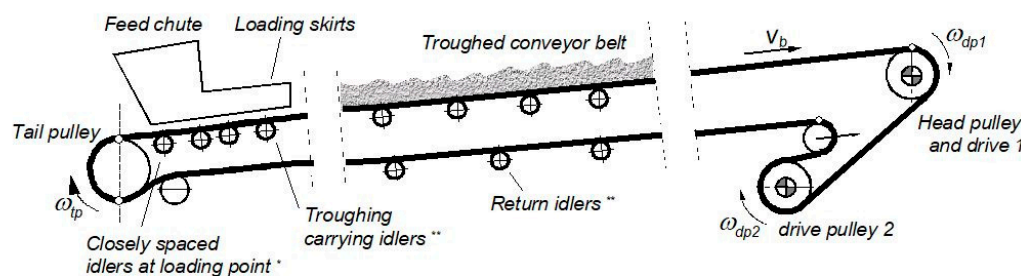


Figure 3. Layout of the main conveyor objects generating motion resistances [61].

Table 1. Parameters of analyzed energy efficient belt conveyor.

Parameter	Value
Conveyor length	600 m
Angle of route profile	2–7°
Material conveyed	Crushed dolomite, density 2100 kg/m ³
Maximum Tonnage capacity	640 t/h
Drive unit	75 kW, 2 pulleys, VFD
Conveyor Belt type	Textile, EP1000/4 (8 + 2), 12,23 kg/m
Belt speed	2 m/s
Conveyor belt's support element—Idlers	energy efficient, rotational resistance 1.2N Carrying idlers: 3 roll, trough angle: 30°, space intervals: 1.2 m Return idlers: 1 roll, space intervals: 3 m,
Belt cleaning device—Scraper resistance	300 N
Ambient temperature	11 °C

As it is presented in Figure 4, positive values of power indicate that even an energy efficient conveyor at the small inclination angle of -2° cannot be used for energy recovery purposes. In the case of the conveyor, where the angle route profile equals -3° , the problem with achieving the average conveyor capacity (400 t/h) occurs in open-pit mines. In the case of the route angle values being between -4° and -7° recovery of energy operation is possible in a sufficiently large range of conveyor capacity.

Taking above into consideration, there are two conditions for the use of the regenerative belt conveyor implementation:

- Mineral deposits located in a hilly terrain and the run-of-mine material is transported downhill—a declining belt conveyor route can be laid out;
- The gravity forces work of the conveyed material significantly surpasses the conveyor motion resistances, which usually can be achieved with the help of a storage bunker at the loading point to maintain the actual high capacity.

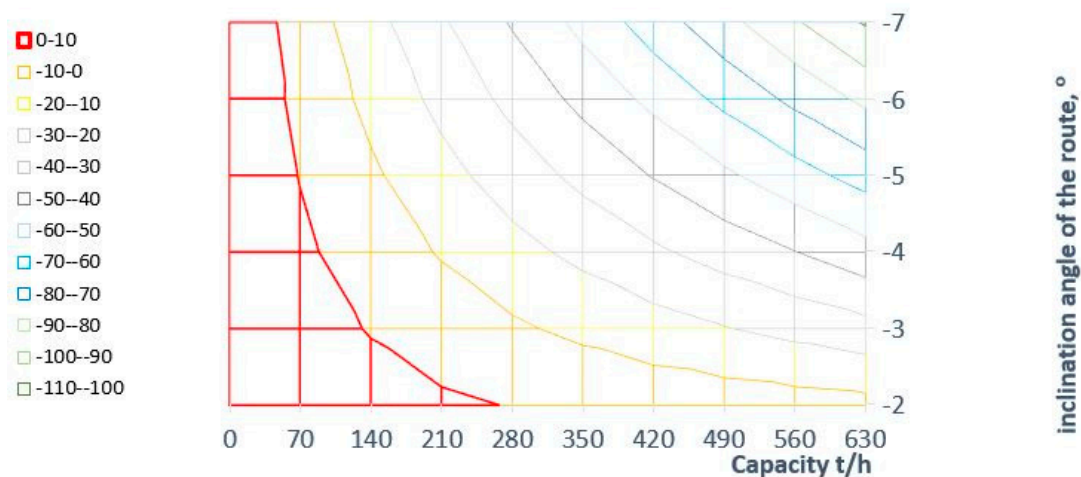


Figure 4. Drive power map for downhill conveyor (exerting at drive pulley shaft); power contours every 10 kW, red grid—no energy recovery area, negative values represent recovered power (calculations: QNK-TT software).

3.2. Recovery of Energy—The Comparison of an Energy Efficient and a Typical Belt Conveyor

In order to indicate a conveyor system, which enables the recovery of energy, the comparison of two alternative conveyors was performed. The first is an energy efficient belt conveyor (Table 1) and the second is a typical belt conveyor, for which idler rotational resistance equals 3 N and the textile conveyor belt parameters are EP1000/4 (8 + 3) and mass is 13.3 kg/m.

The site-specific energy consumption of these conveyors has been presented as a function of amount of transported material and compared with the SSEC of the actual truck (see Tables 2 and 3) and with the gravity force work (Figure 5). It is shown that energy savings may be achieved by using the efficient belt conveyor or increasing conveyor capacity. The higher values of capacity may be achieved by using a storage bunker. The analysis of the conveyor capacity distribution with and without the bunker is presented in Figure 6. The change in the amount of transported material caused by the storage bunker enables a more effective management of the belt filling ratio (the ratio of the actual to the maximum conveyor capacity).

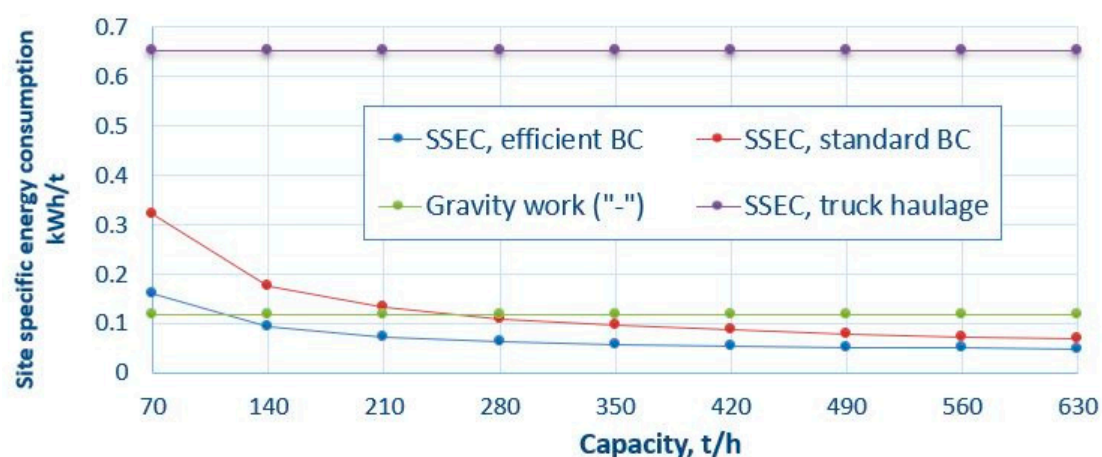


Figure 5. Comparison of the site-specific energy consumption needed to overcome resistance to motion and gravitation forces calculated on 1 metric ton of transported material from the mine departure to the depot (see: Figure 1).

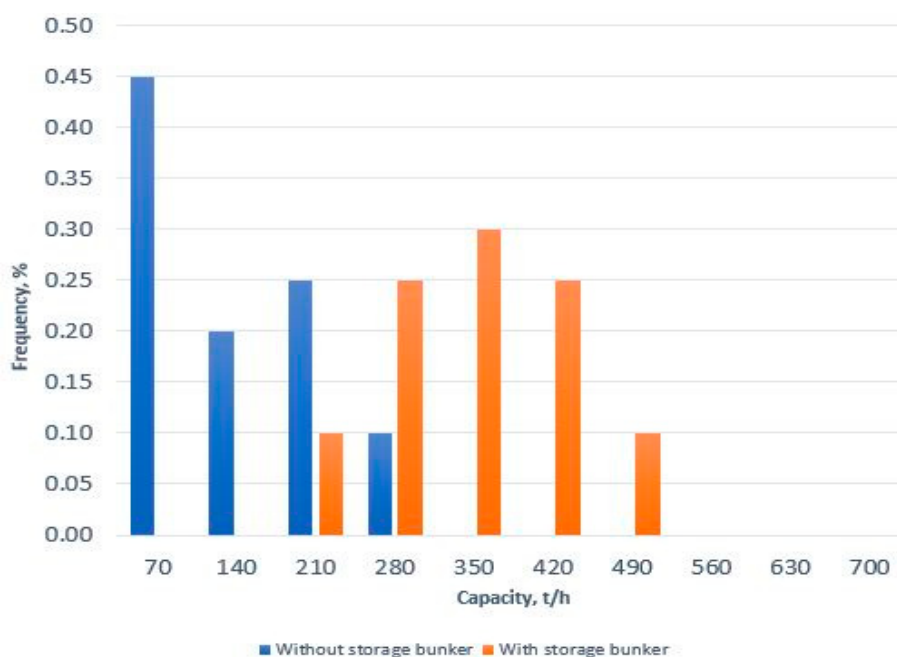


Figure 6. Capacity distribution of transported aggregate by a conveyor for two operational loading scenarios: with and without a storage bunker.

To evaluate the possibility of recovery energy during downhill transportation, four different alternatives have been compared (Table 2). As it occurred, the system storage bunkers with efficient belt conveyors are the most effective solution when it comes to the amount of recovered energy (6MWh).

Table 2. Parameters of analyzed energy efficient belt conveyor.

Parameter	CONVEYOR			
	Typical		Efficient	
	Without Storage Bunker	With Storage Bunker	Without Storage Bunker	With Storage Bunker
Working hours, h	2000	500	2000	500
Idle working hours, h	1300	200	1300	200
Average capacity, t/h	140	350	140	350
Site specific energy consumption, kWh/t	0.178	0.095	0.095	0.057
Gravity work, kWh/t	−0.117	−0.117	−0.117	−0.117
Idle power, kW	21	21	10.0	10.0
Regenerative work	NO	YES	YES	YES
Energy consumption, MWh	27.3	4.2	13.0	2.0
Recovered energy, MWh	−6.1	2.2	2.3	6.0

The comparison of the energy efficiency of the standard belt conveyor and the efficient one indicates that energy efficient components of belt conveyors can significantly reduce the site-specific energy consumption (SSEC) value (Figure 5). The typical conveyor would not recover the energy unlike the efficient one. Furthermore, the storage bunker on the entrance to a conveyor system enables a more effective distribution of mass flowrate. High average capacity of a running conveyor directly influences the energy efficiency of a belt conveyor transportation system. In works [50,51,68], it was proven that the implementation of energy efficient components or conveyor-bunker-conveyor transportation systems result in energy consumption reduction.

For the analyzed case, only the implementation of these two solutions combined (energy efficient conveyor elements and the storage bunker to maintain the high average capacity) would lead to the real possibility of generating the electric energy.

3.3. Energy Efficiency and Environmental Improvements Impact Benefits

Nowadays, the analysis of environmental impact of proposed solutions for belt conveyor transportation system, presented for instance in [47,69], is considered as an essential part of a research. The implementation of regenerative conveyor results in energy and environmental benefits. Firstly, the replacement of the haul truck with the conveyor is an activity oriented on energy efficiency improvement. Therefore, the company may obtain the energy efficiency certificate (white certificate) if the project yields a total energy savings amount equivalent to at least 10 tons (ton of oil equivalent) per year on average [70]. Sum of annual savings of diesel fuel (5.04–5.61 tons—Table 3) and recovered energy (1 ton—estimated based on Table 2) is not enough for the white certificate but may be used for an energy efficiency audits. Secondly, the conveyor operation leads to a lower value of cost per ton of transported material. As an average cost of 1MWh is around EUR 109.27 [71], the total cost of 2 MWh of consumed energy is around EUR 218.56. Taking into account the annual production, the average cost for belt conveyor transportation is EUR 0.0022 per ton*meter. When it comes to haul truck transportation, its cost of EUR 0.054 per ton*meter was assumed following Zajączkowski et al. [72]. The difference in transportation cost between the haul truck and energy efficient conveyor is estimated at around 95%. The similar result of 93% difference in costs for conveyors and haul trucks was achieved in [73] for 762 m transportation length and production capacity of 630 t/h. Last but not least, in comparison to haul trucks which are directly responsible for emissions because they burn diesel fuel, belt conveyors are an indirect source of emissions. Furthermore, the regenerative conveyor enables to reduce air pollutant emissions, because some part of needed electricity is not generated in fossil fuels power plants but by conveyors themselves. Comparing the environmental aspect of transportation system substitutions, it appears that total CO₂ emissions for the mining truck equals 15.73 tons annually (CO₂ factor emission is 2.622 kg/l [74]). The value of CO₂ emissions for efficient conveyors with a storage bunker is 1584 kg (Table 4). It is noteworthy that for downhill conveyors, energy consumption is estimated only for idle operation. Given these points, we can finally focus on the evaluation of reduction of emissions while using recovery of energy for downhill efficient conveyors with a storage bunker. Calculations for annual value of 6 MWh of recovered energy were prepared in accordance with [75] and presented in Table 5. It shows that the implementation of the proposed solution may result in nearly 5 tons of CO₂ reduction annually.

Table 3. Parameters of alternative haul truck transportation for the analyzed site.

Capacity, t	20
Annual distance, km	15,000
Average fuel usage, l/100 km	40
Total fuel usage, l	6000
Density of diesel fuel, kg/l	0.84
Mass of used diesel fuel (~toe), t	5.04
SSEC, kWh/t (by CEMA [76])	0.652
Energy consumption, MWh	65.22
Conversion MWh to toe	5.61

Table 4. CO₂ emission comparison.

Parameter	Mining Truck	Regenerative Belt Conveyor
Emitted CO ₂	15,730	1584
Saved emission	none	4752

Table 5. Reduction of gas emissions due to energy recovered by downhill transportation.

Emission Type	kg/MWh	kg
CO ₂	792	4752
SO ₂	0.704	4.224
NO _x	0.653	3.918
CO	0.285	1.71
dust	0.037	0.222

It must be also noted that regardless of the actual electric energy mix, the replacement of mining trucks with belt conveyors enables a decrease in fossil fuel consumption because electricity is consumed instead of oil or gas, such as compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG). Taking into account the growing share of “green” sources of energy in the national energy mix, this advantage of belt conveyors over diesel trucks grows as well.

4. Conclusions

Currently, the mining industry has to respond to the challenge of energy-related requirements for sustainable development and policy framework. Belt conveying transportation systems have been recognized as a possible direction for an energy efficient implementation. For the comparison of an alternative mode of transportation, the presented site-specific energy consumption (SSEC) indicator should be analyzed with regard to differences of standards compliant routes layout designed for trucks, conveyors or rail vehicles.

While analyzing the replacement dump trucks by belt conveyors, it has been proven that downhill belt conveyor systems can generate energy from the potential gravitational energy accumulated in mined deposits. A mine that implements such solution increases the overall recovery of the mined raw material which follows the sustainable development challenges.

Recovery of energy is possible by implementing a regenerative belt conveyor. However, such transportation system needs to be precisely designed with special focus on:

- conveyor route profile (the inclination angle above 5° is recommended),
- energy efficient components of belt conveyor (the accurate, object-oriented calculations of a belt conveyor resistances to motion are necessary to select the best suited technical solution)
- a storage bunker with a belt conveyor system to keep high capacity and avoid low loading or empty operations (where the regenerative conveyor needs driving).

The presented case study has proven that a regenerative conveyor brings savings in both the overall energy and fossil fuel consumption, transportation costs reduction and gas emissions, noise, vibration and road damage reduction.

All things considered, regenerative belt conveyors, because of their positive influence on pro-environmental performance of an open-pit may become a trademark for sustainable open-pit mines located in hilly terrains and help the mining company to receive social acceptance.

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